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Conceptual Models as Hypotheses in Monitoring Urban Landscapes

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Abstract Many problems and challenges of ecosystem management currently are driven by the rapid pace and spatial extent of landscape change. Parks and reserves within areas of high human population density are especially challenged to meet the recreational needs of local populations and to preserve valued environmental resources. The complex problem of managing multiple objectives and multiple resources requires an enormous quantity of information, and conceptual models have been proposed as tools for organizing and interpreting this information. Academics generally prefer a bottom-up approach to model construction that emphasizes ecologic theory and process, whereas managers often use a top-down approach that takes advantage of existing information to address more pragmatic objectives. The authors propose a formal process for developing, applying, and testing conceptual models to be used in landscape monitoring that reconciles these seemingly opposing perspectives. The four-step process embraces the role of hypothesis testing in the development of models and evaluation of their utility. An example application of the process to a network of national parks in and around Washington, DC illustrates the ability of the approach to systematically identify monitoring data that would both advance ecologic theory and inform management decisions.

Keywords Conceptual ecologic models · Model evaluation · National Capital Region Network · Stressor-response · Urban ecology · Vital signs monitoring

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Introduction

Environmental management has evolved over the past 20 years from a view emphasizing single, discrete stressors affecting a limited number of species to an ecosystem approach that addresses the multivariate implications of environmental change (Kurtz and others 2001; Sutter 1999b). Conservation concerns currently range from assessing the status of endangered species to evaluating the impact of multiple stressors on biodiversity and ecosystem functioning (Vinebrooke and others 2004; Weins and others 2002). In response to this broadening of emphases, a number of national-level efforts have emerged to establish ecologic indicators for monitoring the condition and trends in the nation's ecologic resources (Heinz Center 2002; National Research Council 2000). Integration of this monitoring information into ecosystem management has proved to be a daunting task.

The growing recognition that human activities are a central element of environmental change further complicates the design of effective management regimes. A small but vocal cadre of scientists has articulated the view that human activities can no longer be viewed as exogeneous, perturbing forces, but must be incorporated into empirical and theoretical studies to account fully for the exchange of material and energy within the earth's ecosystems (e.g., Pickett and others 2001). Urban landscapes are an obvious choice for the development of such a theory, yet from 1995 to 1999, less than 1% of the papers in nine leading ecologic journals described work conducted in urban environments (Collins and others 2000). The National Science Foundation recognized this gap in the science by establishing two long-term ecologic research sites within the urban environments of Baltimore and Phoenix (Parlange 1998).

The conservation community also has paid inadequate attention to areas in which large numbers of people live and work. For example, Miller and Hobbs (2002) found that studies conducted in urban settings accounted for fewer than 6% of the papers published in the journal *Conservation Biology*. This low publication rate is inconsistent with the reality that the majority of global conservation priority regions are located in areas of high human population density (Cincotta and others 2000). Small urban parks play a vital role as biologic refugia, migration rest stops, and dispersal corridors, all of which have been shown to greatly enhance regional biodiversity (Falkner and Stohlgren 1997). Healthy native habitats in densely settled areas also offer considerable social, economic, and educational benefits (Forsyth and Musacchio 2005).

The lack of attention to ecologic and conservation theory in urban settings is particularly troubling given the variety of pathways through which urbanization can alter ecologic processes. Scenic beauty and recreational opportunities are affected not only by urban development adjacent to parks (Harris and others 1997), but human pressures also are at least partially responsible for the population declines of more than 50% of the species listed in the U.S. Endangered Species Act (Czech and others 2000). Moreover, hydrologic changes associated with urbanization have resulted in the loss of wetland tree species, the degradation of riparian and in-stream habitat, and the eventual deterioration of water quality (Groffman and others 2003).

In addition, urban development and associated edge effects can have profound effects on temperature (Chen and others 1993; Oke 1988), precipitation (Jauregui and Romales 1996), and air pollution (Driscoll and others 2003, Mueller and others 2004). These altered environmental conditions have been linked to biotic responses in vegetation structure (Ranney and others 1981), composition (Chen and others 1992; Marshall 1989), and demographic processes (McDonald & Urban 2005; Meiners and others 2002). As a consequence, management of the biologic, recreational, and scenic resources in urban parks requires a broad understanding of the complex interactions between multiple environmental stressors.

In general, national-level monitoring programs (e.g., US Environmental Protection Agency's Environmental Monitoring and Assessment Program, Environment Canada's Ecological Monitoring and Assessment Network, U.S. National Park Service's Inventory and Monitoring Program) recognize the need for integrative assessment of multiple forces of change (Liu and Taylor 2002). However, they have been challenged to accomplish this goal within fixed budgetary constraints. Common concerns confronted by long-term ecologic monitoring programs include poorly specified objectives, a piecemeal approach to selection of monitoring indicators, and nebulous connections between the data being collected—including both the resources and their stressors—and management decisions (Woodward and others 1999). Under these circumstances, conceptual models have offered a useful tool for designing synthetic strategies to monitor the consequences of ecosystem change (Busch and Trexler 2003; Sutter 1999a).

Conceptual ecologic models provide a simplified overview of ecosystem structure and function. Effective models can take the form of any combination of narratives, tables, and graphic depictions, but should be (1) easy to communicate and transparent to multiple audiences, (2) inclusive of key ecosystem attributes and critical agents of change, and (3) flexible in design (''adaptive'') to allow for response to novel events and findings (Haefner 1996; National Research Council 2000; Noon 2003; Woodward and others 1999). In representing multiple activities with varied direct and indirect linkages, models with modular components can provide a basis for organizing and conducting efficient environmental assessments (Sutter 1999a, 1999b). Well-designed conceptual models can be especially valuable for monitoring by informing the logistics of sample designs (e.g., addressing questions of variable selection, co-location, co-visitation, spatial and temporal scaling), by helping to ensure early warning/detection of environmental change, and by creating a structure for translating monitoring data into management actions within an adaptive management framework (*sensu* Christensen and others 1996).

This article provides an outline for constructing conceptual models that can be used to monitor environmental change in urban landscapes. The approach was developed for the National Park Service's Inventory and Monitoring Program for the National Capital

Region Network (NCRN) of parks within the greater Washington, DC metropolitan area, and we present the NCRN example as a case study.

Conceptual Models and Hypothesis Testing

A major challenge in the development of conceptual models for monitoring programs is to communicate complex ecologic relationships to audiences with vastly different needs, levels of expertise, and expectations. Nontechnical audiences typically prefer and best understand highly aggregated models that clearly demonstrate pragmatic links between resources and the factors that threaten resources. In these models, ecologic detail and structural accuracy can be compromised to include social or legislative mandates, and the emphasis is on communicating a few key linkages clearly and simply. The model-building approach is often top down in an effort to incorporate priority management concerns and preexisting data on the ecosystem trends related to these concerns. These models can be ideal for demonstrating connections between ecologic indicators and the resources they reflect, but the models typically lack the rigor and detail needed for unambiguous interpretation of monitoring observations.

Scientific audiences usually prefer more detailed models that place greater emphasis on the understanding of relevant ecologic processes. Conceptual models are constructed using a bottom-up approach that combines ecologic theory with observations in a more predictive framework. In some cases, these models are mechanistically and structurally correct and can be converted easily into quantitative models. The models can better reflect quantitative hypotheses, such as the shape of a functional relationship between ecologic parameters, and they are well suited to identifying key monitoring measurements. However, they may be poorly suited for communication with nonspecialist audiences, who may fear that the level of detail obscures key linkages between an indicator and the resource it reflects.

We propose that the tension brought to the modeling process by these seemingly conflicting viewpoints is artificial and unproductive. There is a growing literature on the explicit and structured integration of the concerns and objectives of environmental professionals into ecologic models (e.g., van den Belt 2004). This integration is too often hampered by poor communication between the varied stakeholders engaged in the process. We argue that all models are, *per se*, testable hypotheses, and that every decision in the model development process is based on a hypothesis about

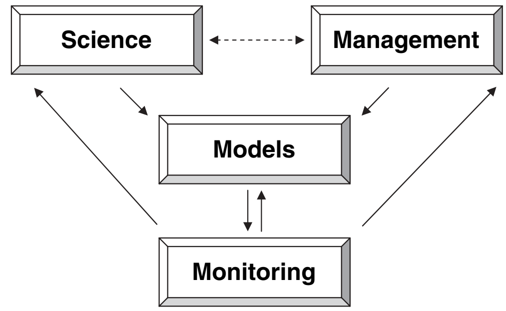

Fig. 1 Working together, science and management can use conceptual models to inform monitoring that contributes to both scientific understanding and management decision making

the system, whether that hypothesis is stated explicitly or not. The formal statement of the hypotheses involved at each stage of model construction could serve as a common language to bring together diverse communities to build conceptual models for monitoring programs that serve a variety of needs (Fig. 1).

The following four-step process outlines an approach to model construction that satisfies management needs to preserve valued resources, anticipates the undesirable consequences of environmental change, and advances our scientific understanding of issues threatening ecosystem sustainability. Specifically, the approach uses a related set of hypotheses to aid model construction: Are resources sustainable given current management practices? If not, what stressors are inducing resource change? Is the modeled correspondence between resources and stressors sufficient for management purposes?

Because the effects of ecosystem change often are manifested in unexpected ways, this process is not linear, but relies on continual iteration to ensure that critical processes are understood and the best management model is achieved. We illustrate the process using an example from our work with the NCRN of parks in and around Washington, DC.

Monitoring of National Capital Region Parks

As a result of the Natural Resource Challenge, the National Park Service (NPS) is implementing a series of programs designed to provide a stronger scientific basis for management actions (Kaiser 2000; NPS 1999). The Inventory and Monitoring (I&M) program was initiated in 1990 to help fulfill this mission at more than 270 national parks organized into 32 networks sharing similar physiographic and ecologic characteristics (Fancy 2002). A primary goal of the I&M program is to compress the vast amount of information being gathered into scientifically sound but understandable formats. Conceptual models play a key role in this effort.

The NCRN is made up of the following 11 parks within the District of Columbia, Maryland, Virginia, and West Virginia: Antietam National Battlefield, Catoctin Mountain Park, Chesapeake and Ohio Canal National Historical Park, George Washington Memorial Parkway, Harpers Ferry National Historical Park, Manassas National Battlefield, Monocacy National Battlefield, National Capital Parks—East, Prince William Forest Park, Rock Creek Park, and Wolf Trap Farm Park. Altogether, these parks cover more than 30,000 ha spanning four physiographic regions: Atlantic Coastal Plain, Piedmont Plateau, Ridge and Valley, and Blue Ridge. They include long linear parkways, battlefield sites, and relatively large intact forest preserves.

Nearly all the park land in the NCRN lies within the rapidly developing Potomac watershed, which is a major contributing source of water to the Chesapeake Bay. Although the majority of the watershed is agricultural and forested, urban growth in the region is among the fastest in the country. Between 1973 and 1996, the rate of urban expansion around the District of Columbia was approximately 22 km^2 per year (Masek and others 2000). From 2000 to 2003, the U.S. Census Bureau reported a 30.7% population growth rate in Loudoun County (40 km west of the District of Columbia), making it one of the fastest growing counties in the nation.

The population density of the region results in extremely heavy use of the parks. Although they comprise only 1% of the total NPS lands, NCRN parks receive approximately 14% of the total NPS visitations (NPS 1999). The George Washington Memorial Parkway alone had more than 7 million recreational visits in 2004, making it the sixth most popular unit in the National Park System (Barna and Gaumer 2005). Many of the park management issues in the NCRN are related to anthropogenic stressors associated with the rapidly urbanizing landscape.

Step 1: Casting a Broad Net

The first stage of our proposed model development process is to gather as much relevant information as possible pertaining to the ecologic functioning and likely management concerns of the system of interest (Fig. 2). The process is aided by identifying similar landscapes susceptible to similar management issues. These example systems provide a basis for identifying resource targets of concern (or end points) and the relevant environmental stressors that may induce undesirable change in these end points.

This initial list should be as inclusive as possible. For example, the plant pathogen sudden oak death (*Phytophthora ramorum*) is an emerging forest disease that has reached epidemic levels in parts of California and southern Oregon (Rizzo and Garbelotto 2003). Although sudden oak death has not yet spread across the entire United States, an alarming number of uninfected forests are potentially susceptible (Meentemeyer and others 2004). A broad net developed at the outset of an integrative monitoring effort will help to flag novel system components, such as pathogens without historical precedent in the study system. Although not currently a concern, these potential stressors may become significant management challenges. If they are incorporated into the conceptual models, the models can act to guide monitoring that is not just reactive to current management concerns, but also anticipatory of future challenges.

For the NCRN effort, we took advantage of the collective efforts undertaken by other NPS I&M networks of parks to identify high-priority ‘‘vital signs’’ (Fig. 2b), defined as ‘‘selected physical, chemical, and biologic elements and processes of park ecosystems that represent the overall health or condition of the park, known or hypothesized effects of stressors, or elements that have important human values’’ (Fancy 2002, p. 2). Among the 32 networks of parks covering the nation, 12 were funded in 2002, with an additional 10 networks funded over the following 2 years (total of 185 parks). The development of monitoring plans for these parks has generated a wealth of information on the natural resources, the stressors potentially affecting those resources, and the vital signs used to track the environmental resources and stressors within the nation's national parks.

The NPS has constructed a database of high-priority vital signs identified by the first group of networks to develop comprehensive monitoring plans. The process used to select these vital signs involved extensive literature reviews and consultation with park resource managers and scientists from the NPS as well as more than 150 universities and other federal and state agencies. The database contains lists of vital signs and related field measures for networks and individual park units. Additional information available directly from the networks includes raw data collected during field studies and example monitoring protocols. The knowledge and experiences gained from other networks in the development of their own monitoring plans served as a broad net capturing varied issues of potential importance to the development of conceptual models for the NCRN.

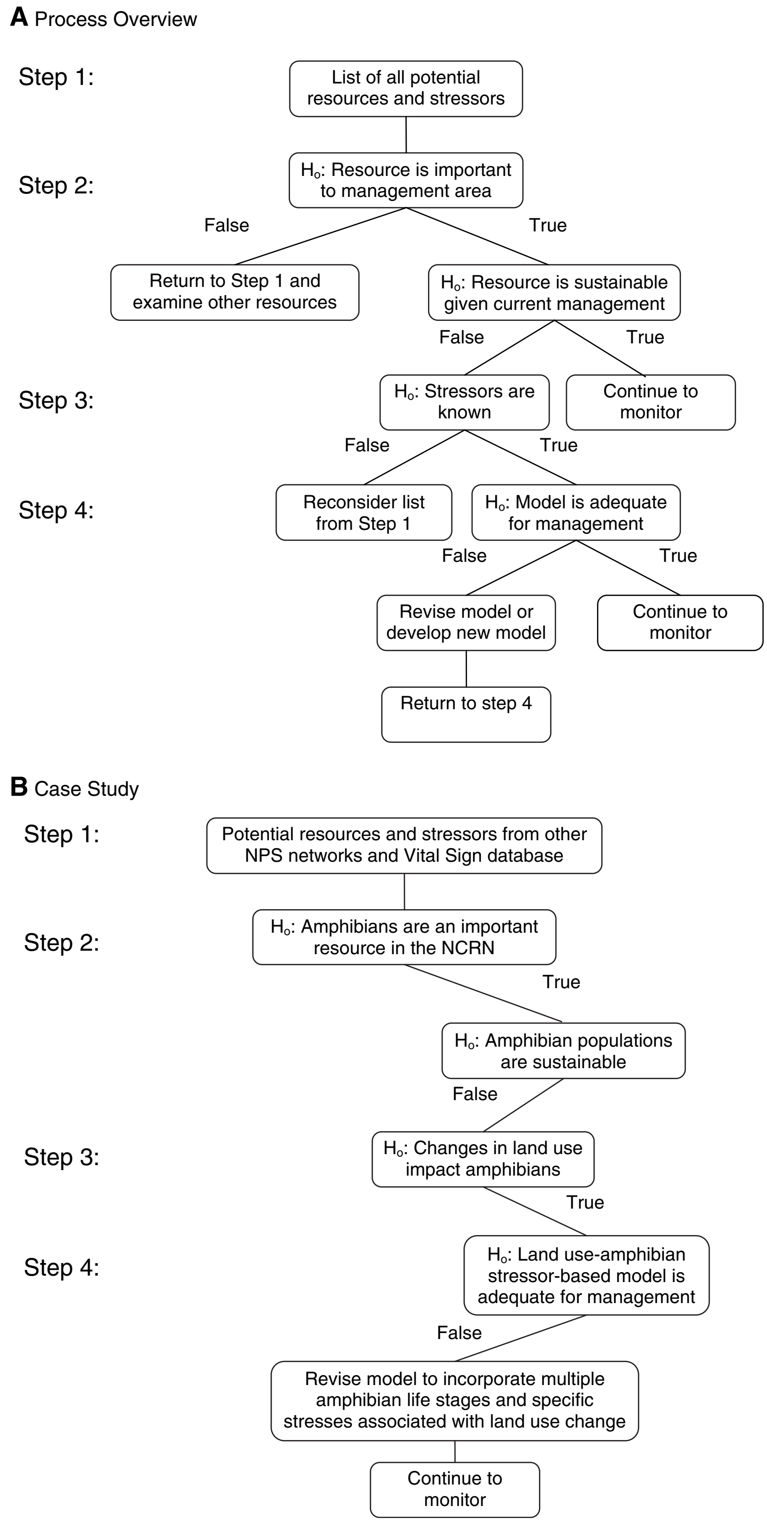

Fig. 2 Conceptual model development process. (a) Process overview. Each step requires consideration of model material in a hypothesis-testing framework. (b) Example application of the process for National Park Service (NPS) monitoring in the National Capital Region Network (NCRN)

It is not logistically or financially feasible to address all of the potential concerns included in the broad net for each and every park in the NPS system. In step 2, the broad net is refined to identify priority issues for the NCRN.

Step 2: Narrowing the Focus

The second step in developing the models is to identify specific resources of concern to the management area and to assess the long-term ecosystem sustainability of those resources. The operational assumption (or ''null hypothesis'') is that current management practices are sufficient to maintain sustainability, and that current monitoring information will identify new adverse effects in a timely manner. To evaluate this null hypothesis, three important questions must be addressed: Have the critical resources been identified in step 1? Are these resources properly managed and monitored? What stressors (both current and new) may adversely affect ecosystem sustainability through time?

This second step uses local data and expertise to filter the information from the broad net and to identify local systems of concern. At this stage, linkages are not yet drawn between the different components of the system. The various components are simply identified at a coarse level. Where little information is available on the status and trends of a key resource, monitoring may be established immediately to test the null hypothesis of sustainability. This perspective ensures that even in the absence of process-based understanding, broad-scale, long-term monitoring will be in place to detect slow incremental changes that may precipitate irreversible system change (Weins and others 2002).

Using information from the national vital signs broad net, a 27-member Scientific Advisory Committee (SAC) prioritized the resources and stressors of greatest concern to the NCRN. On the basis of the national-level information and local knowledge on unique resources, the SAC grouped the region's resources into a few broad categories: four primary ecosystem domains (air/climate, geology/soils, water, biota) interacting through changes in ecosystem pattern and process. The SAC also summarized the six major stressors to these resources: land use dynamics, invasive species, infestations/disease, chemical contaminants, air pollutants, and climate change.

A network-level scoping workshop then was held to review and refine these preliminary hypotheses regarding the resources and stressors of concern to the NCRN (Koenen and others 2002). More than 100 individuals participated in the workshop, including park staff and representatives from more than 20 partnering agencies and organizations. Breakout groups at the workshop separately considered each of the broad resource categories and developed detailed lists of the specific resources, major stressors and monitoring objectives related to each. Given the close proximity of the NCRN parks to major metropolitan areas, it was not surprising that the majority of concerns raised related to the urbanization of the landscape. It was proposed that monitoring data should be collected to test the null hypothesis of sustainability for each of the resources listed by the workshop breakout groups.

Step 3: Deriving Resource-Stressor Relationships

In the third step, the separate lists of resources and stressors are combined into scenarios that describe specific threats to ecosystem sustainability. The rapid, diverse changes now being observed in many ecosystems require monitoring studies to interpret observed trends and recommend appropriate management actions (DeAngelis and others 2003). Simple box-and-arrow diagrams tracing the pathways from specific stressors to putative ecologic damages provide an effective means for linking monitoring data to management (Busch and Trexler 2003; Noon 1999). The usefulness of these stressor-based models depends on their ability to depict the relationships among resources of interest, potential agents of change, and their respective monitoring indicators. The depicted relationships are new hypotheses to be verified by monitoring studies and thus are useful for specifying relevant monitoring protocols. In addition to their relevance to management, the models are effective communication tools, informing diverse audiences of the approach being used to understand the adverse consequences of environmental change.

The stressor models are not intended to provide a systemic understanding of ecosystem dynamics. Rather, the models attempt to link specific ecosystem changes with relevant stressors that may be inducing those changes. These relationships highlight priority measurements, allowing for efficient sampling under limited budgets, and therefore guide the design of parsimonious long-term monitoring protocols. In addition, the cause–effect hypotheses posed by the models provide early guidance for management when confronted with novel stressors. These causal links between resources of interest and potential agents of change can be used to inform preliminary management decisions, perhaps even before the detailed mechanisms that underlie the relationships are fully understood. The rapid management response to environmental stressors is particularly critical for the conservation of the small resource units found in urban settings.

The first effort to piece together the descriptions of NCRN resources and stressors into a coherent model made use of the SAC material in a Jenny-Chapin holistic framework. This approach, originally proposed by Jenny (1941), emphasized the five state factors that control ecosystem processes within soils. This concept was later extended to describe how these state factors influenced ecosystem sustainability by constraining

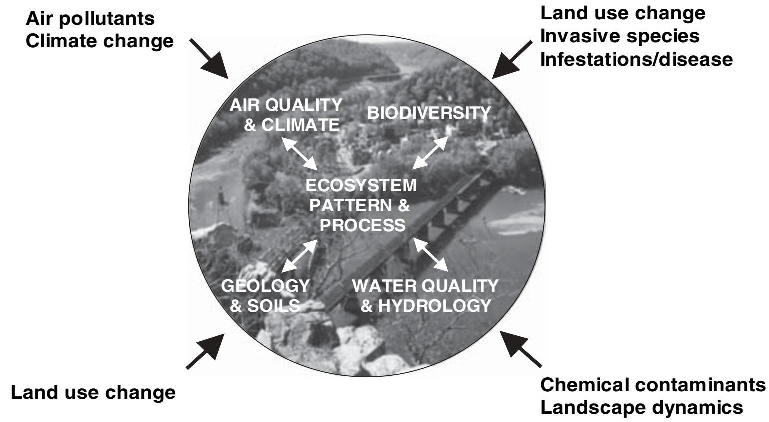

Fig. 3 National Capital Region Network (NCRN) overview model (modified from Miller 2005). Using a Jenny-Chapin framework, this conceptual model depicts the relationships among broad ecosystem resource categories and those anthropogenic stressors of greatest concern to park management

endogenous ecosystem processes (Chapin and others 1996). Miller (2005) first applied the Jenny-Chapin approach in an NPS setting and showed how it can be used to guide the development of additional conceptual models. We modified the model further to consider a more complete representation of ecosystem resources including soil, air, water, and biota (both terrestrial and aquatic). The relationships among these resources were considered dynamic and interactive, governing ecosystem processes, but also being responsive to ecosystem change.

We also focused on those external constraints that most concern park management, mainly anthropogenic stressors (Fig. 3). Primary stressors are those that directly influence a particular resource. Secondary stressors can affect a resource indirectly through the interaction with relevant ecosystem processes and their pattern. For example, the model depicts the potential direct influences of land use change, invasive species, and infestations/disease on biota. The model also considers indirect biogeochemical influences on biota associated with chemical contaminants entering the ecosystem through the water or air resource domains.

In addition to this overview model, conceptual models for specific resources were constructed following the deliberations of workshop breakout groups. For example, the biotic resource group determined that amphibians were a focal resource of concern due to recent observations of their decline in the region, as measured using the U.S. Geological Survey's Amphibian Research and Monitoring Initiative (ARMI) site occupancy metric (MacKenzie and others 2003). Similar declines in amphibian populations have been noted for more than 200 species throughout the world, with global reports of at least 32 species extinctions (Alford and Richards 1999; Blaustein and Wake 1990; Houlahan and others 2000).

An advantage of the ARMI approach to monitoring is that it allows the incorporation of covariates to test specific hypotheses about factors influencing the distribution of amphibians (MacKenzie and others 2003). Collins and Storfer (2003) have grouped the hypothesized causes for recent amphibian declines into two major categories. The first category includes factors general to the overall biodiversity crisis: habitat destruction, alteration and fragmentation, invasive species, and overexploitation. The second category includes climate change, chemical contaminants, and emerging infectious disease. The often subtle mechanisms by which this second group of factors influence amphibian populations is poorly understood, but likely include synergistic interactions with more direct factors related to land use change.

After considering the broad net and local evidence, the biota technical working group hypothesized an association between land use and amphibian populations in the NCRN parks. A simple box-and-arrow model depicts this potential relationship (Fig. 4), which is guiding the long-term measurement of a select group of vital signs: land cover, landscape condition, visitor use, amphibian diversity, and site occupancy. The model is supported by several empirical studies investigating the negative influence of urbanization on amphibian populations in Maryland (Findlay and Bourdages 2000) and the Washington metropolitan area (Volstad and others 2003). However, the model does not provide information on the specific mechanisms by which these factors are related. A more detailed understanding will be necessary for effective management of amphibians in areas where urban development will continue to have an impact on these ecologic resources.

Step 4: Evaluating Model Usefulness

The process of model development described in the previous steps will be based, of necessity, on uncertain,

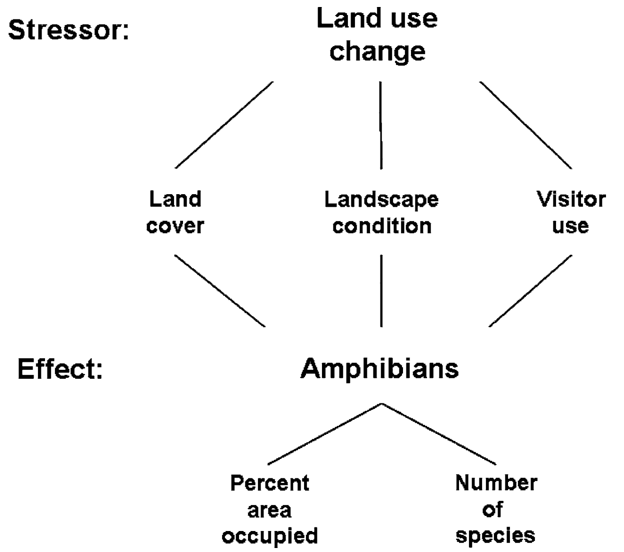

Fig. 4 Stressor-based model representing the potential influence of changes in land use on amphibian populations in the National Capital Region Network (NCRN). The broad vital sign measures selected for monitoring (land cover, landscape condition, visitor use, amphibian occupancy, and diversity) will provide some information on these relationships through time. However, the model does not provide information on the specific mechanisms by which these two factors are related

incomplete, and often conflicting information. It is essential, then, that the performance of the models be continuously reexamined. In this sense, the development of a conceptual model is an ongoing and iterative process (Jackson and others 2000).

Model performance can be evaluated through a variety of quantitative and qualitative measures. For example, the correspondence between model behavior and observed system behavior can be described in terms of model adequacy (the proportion of the observed system behavior predicted by the model) and model reliability (the proportion of model behavior corresponding to observed system behavior) (Mankin and others 1975). Gardner and Urban (2002) have noted that errors and uncertainty in model development and data collection compound the problems of model–data comparisons, making an absolute statement of model adequacy and reliability problematic.

We propose a series of three criteria for assessing the value of a model for management applications:

1. *Correspondence criterion.* Model revision may be warranted if long-term monitoring data fail to provide substantial correspondence between model predictions and monitoring observations. For instance, a perfect model makes predictions with 100% accuracy. Substantial departures from this perfect correspondence are indicators of model failure showing that the relationships proposed in the model should be reevaluated.
2. *Applicability criterion.* Model revision may be warranted if management action requires additional information or a more detailed understanding of ecosystem response to environmental perturbations. For instance, knowledge of thresholds and the magnitude of ecosystem change resulting from a small increase in stressor levels can be critical for designing cost-effective remediation efforts.
3. *Reliability criterion.* Model revision may be warranted if the model provides a broad set of responses beyond the range of patterns that have been historically observed. A failure to confirm a large portion of model predictions could indicate an unreliable model. Alternatively, it could indicate a failure of the available data to capture the true breadth of system behavior.

Model failures are as important as successful model performance because failures indicate where current knowledge is inadequate or in error. The failure of a model to meet any of our three criteria also falsifies the null hypothesis that present understanding of ecosystem behavior is sufficient for management purposes. For example, if the model components do not significantly covary once data become available, then some important pieces of the puzzle have been missed. Ultimately, the process of identifying model errors and making necessary refinements results in a parsimonious set of models that identify the condition of key ecosystem resources, provide an overview of the significant interactions affecting those resources, and explore more detailed mechanisms for the small subset of ecologic processes deemed most critical for protecting priority resources.

Returning to our example for the NCRN, land use change as a stressor cannot be represented as a simple, single-variable effect. Amphibian populations illustrate this problem, being affected by the alteration of hydrologic regimes, the fragmentation of habitat, the introduction of predators, or any of a number of other pathways associated with the urbanization process (Table 1). In addition, we should anticipate that amphibians may respond in novel fashion to the continued increase in stressors associated with increased land use effects (Table 1). The life histories, dispersal abilities, and physiologic tolerances of these organisms make them good indicators of local and regional ecosystem change (Semlitsch 2003), but their susceptibility to multiple interacting stressors at many life history stages also make for a management challenge. Without understanding more about the specific mechanisms by

Table 1 Evaluation of adequacy of land use–amphibian model[a]

Stressor (land use change)	Effect (amphibian)
Roads (new, increased traffic)	Reduction in diversity
New or elevated disease/predators/exotics	Change in generalist:specialist ratio
Illegal harvesting	Increase in tolerants and nonnatives
Contaminants (e.g., pesticides, road salt)	Change in timing of breeding
Habitat modification and loss	Mutations
Isolation/fragmentation	Population declines
Noise pollution	Loss of genetic diversity
Flow regime	Disease
Drought/flooding	Change in migratory patterns

[a] Land use change in the National Capital Region Network (NCRN) stresses amphibian populations via a variety of pathways (list on left), triggering a variety of potential responses (list on right)

which land use change influences amphibians in the NCRN, managers have few options for remediation even if significant correlations are observed. In short, the land use–amphibian model (Fig. 4) passes the correspondence criterion (i.e., there is a statistically significant correspondence between land use and amphibian site occupancy), but fails the applicability criterion, so a refined model is warranted.

In response to these uncertainties, we propose a stage-structured population model that considers the multiple stages of the amphibian life cycle (Fig. 5). In this model, the specific stresses associated with urbanization are assigned to the specific biologic processes they potentially affect. For example, urbanization may limit dispersal through the construction of additional roads and the increase in traffic. Alternatively, urbanization may result in contamination or reduction of the ephemeral springs required for successful amphibian reproduction. Unlike the original model (Fig. 4), which is too general to inform specific management actions, these scenarios provide details that are within the control of park managers. For example, at least one of the NCRN parks (Rock Creek Park) is evaluating the potential benefits of creating

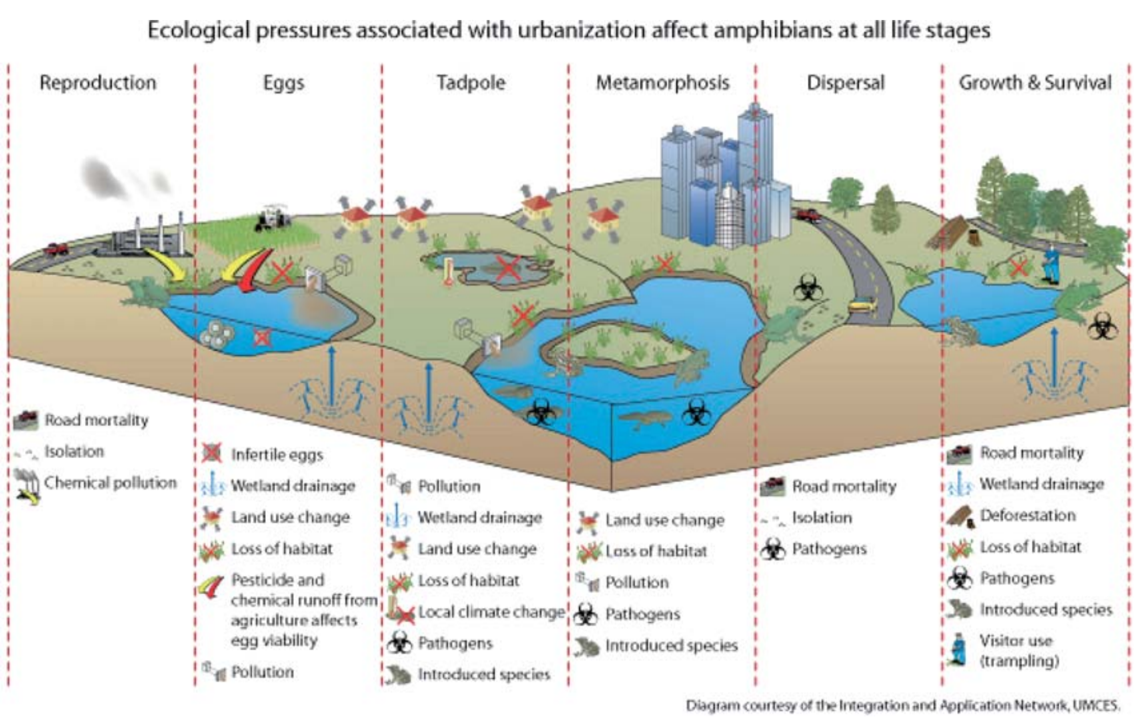

Fig. 5 Revised amphibian–land use change model. Land use change can influence amphibians through a variety of mechanisms, and amphibian response can occur at different stages of the life cycle. The model can be used to guide monitoring protocols that provide information directly relevant to management actions

artificial ephemeral pools. Monitoring data linked to our detailed conceptual model could help establish the potential of this management action to restore amphibian resources.

The level of detail of this new conceptual model is justified by the preliminary finding that amphibian populations are decreasing in the context of increasing urbanization. This initial finding identifies a gap in understanding that can be used to attract additional attention, and perhaps additional funding, to promote and support more intensive research and more focused monitoring. A monitoring strategy guided by this model development process is adaptive, changing in response to new needs and the emergence of new environmental issues. The initial models serve to establish core protocols needed for adequate evaluation of long-term trends, whereas model refinements inform the implementation of additional monitoring protocols. The procurement of funding needed to support these new protocols is aided by the results of the long-term studies initiated to detect and measure trends in critical resources.

Conclusions

Urban landscapes are highly dynamic environments. The management of multiple ecosystem resources in these diverse land use settings demands an enormous quantity of information. Our approach provides a framework for efficiently gathering information on ecologic status and trends using conceptual models. The approach combines scientific theories and data with pragmatic management considerations through a hypothesis-based process of model development. The process improves environmental monitoring by systematically identifying desired monitoring end points. In some instances, these end points may be quite apparent, with the process simply providing a rigorous justification for their selection. In other instances, the process of building models may uncover issues that had otherwise been obscured. In all instances, the resulting monitoring protocols should provide data that both improve scientific understanding and inform management decisions, thus further strengthening the link between environmental theory and management.

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